Evolution of a Building Type: 
The Case of the Multi-Storey Garage

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A great variety of generic designs for multi-storey garages emerged in the 1920s and '30s, some of which raised the cars to the upper levels with elevators, others of which were equipped with ramps. The elevator garage survived until after World War II but today it has almost completely disappeared from America and Europe. Out of the great flowering of inter-War designs of ramp garage, many also vanished, and by the 1960s the field was dominated by one particular layout with split-levels and so-called d'Humy ramps. This paper argues that garages provide a particularly clear cut and instructive example of the evolution of a building type under the pressures of a changing economic, social and technological environment. A few simple quantitative measures can be used to compare the relative 'fitness' of different designs at successive points in time. The paper uses historical data on these measures, and also makes comparisons, on a common basis, of a range of specially designed theoretical garage buildings. The analysis demonstrates the reasons for the success of certain designs and the failure of others. It is suggested that this historical process has some affinities with what is known by Darwinists as evolutionary radiation, when a new unoccupied environment is colonised by a single species that rapidly evolves into a variety of different forms.

Keywords: Multi-storey garages, History, Evolutionary radiation, Configurational analysis

1. The emergence of the multi-storey garage in the early 1900s

In the years immediately before the First World War an entirely new type of building appeared in American cities: the multi-storey parking garage.¹ Car ownership grew rapidly in the US in the early part of the century, from under half a million in 1910 to more than 8 million by 1920 (United States Department of Commerce, 1975). The first automobiles were expensive and fragile, with open tops, and paintwork that was not as weather-resistant as today's finishes. They were generally kept indoors, and put into storage for the winter (Jakle and Sculle, 2004). At first old buildings were converted for the purpose. Some of the earliest purpose-built garages were erected by private motoring organisations such as the Massachusetts Automobile Club, whose three-storey building was opened in 1902. Automobile dealers kept their stock in garages. Other garages were built in wealthy residential areas where the new car owners were concentrated, or near expensive hotels. In some of these structures, cars were stored on floors above ground.
By the early 1920s larger cities were already experiencing traffic congestion in their central streets, exacerbated by kerbside parking. In Chicago the situation in the Loop was such that proposals were being made to raise all sidewalks to upper levels so as to free up more road space (Showalter, 1923). Los Angeles, which had more cars per person than any other city at this period, experienced a serious crisis in 1920 that resulted in a temporary ban on street parking downtown (Bottles, 1992). It was in this context that a new market appeared for multi-storey buildings devoted to daily or short-term parking, by commuters or shoppers. Seven large high-rise garages were built for example in LA between 1923 and 1928 (Longstreth, 1997).

Some of the earliest parking buildings raised the cars to the upper levels with modified freight elevators. Garages were also built with ramps. The ramp buildings were of a great variety of different designs: with straight or helical ramps; with the ramps placed inside the building, on the exterior, or in central courtyards; with split level floors connected by half-length ramps - each generic layout found in several variants. I will go into more detail later. In Europe, few multi-storey garages were built before World War II, one notable exception being the giant Autorimessa in Venice, designed by Eugenio Miozzi and completed in 1934. The subject nevertheless attracted considerable pre-War interest among European engineers, of whom the most prominent was Professor Georg Müller, 'the pioneer of the modern garage' and author of Grosstadt-Garagen, the first book on the subject, published in 1925. Many theoretical designs were proposed, and numerous patents were taken out. Müller lists 35 US and 6 European patents up to 1924, the first of them awarded in 1913.

The elevator garage survived until the 1960s, but soon after that almost completely vanished from both Europe and America. Out of the great diversity of pre-War types of ramp garage, many were also abandoned by the late 1950s; and the majority of garages then operating in America were designs with split levels and so-called D’Humy ramps (Ricker, 1957: 110). Why did this happen? In this paper I argue that we have here a particularly clear-cut and instructive example of the evolution of a building type, under the pressures of a changing economic and technological environment.

2. A case study in the evolution of a building type

Multi-storey garages are not, it must be admitted, the most interesting or challenging type of building from an architectural point of view. True, they have on occasion attracted the attention of leading names, as for example Paul Rudolph’s sculptural Temple Street garage in Newhaven, Connecticut, or Louis Kahn’s project for cylindrical fort-like parking towers in Philadelphia. In general though, as The Architectural Record (1958: 181) remarks, ‘Parking garage operators ... assign “architecture” to the outer six inches of their buildings.’ The very simplicity of garages however makes them an ideal subject for a semi-quantitative evolutionary analysis. Evidently, they have just one basic function: to provide space in which to park cars on upper floor levels (as well as on the ground). Some means are needed to get the cars to these positions, and to retrieve them again, in both cases as rapidly as possible although there can be further considerations relating to access, as we shall see). In general,
these being utilitarian structures, many of them run for profit, the costs of both construction and operation need to be kept low. These various requirements could possibly be combined into a single objective function, capable of mathematical optimisation - although no attempt is made to do so here.

The word 'evolution' should be used cautiously in relation to buildings (Steadman 1979). There has been some interest amongst architectural researchers in computer-based 'evolutionary design methods', where candidate designs are varied at random, evaluated, selected, varied again and so on in a cyclic process, loosely analogous to natural evolution, but speeded up in the laboratory of a computer simulation (Frazer, 1995). The purpose is to arrive at the design for some particular individual building. In this paper, by contrast, I consider a process of gradual change in the form and internal arrangement of a type, taking place over decades, and involving thousands of real buildings actually tested in use and in the marketplace. One of the dangers of applying biological analogies simplistically to the 'evolution' of building types is that the deliberate intentions of individual architects and engineers are thereby underrated and overlooked. If types of building can be said to evolve at all, this is most definitely not - at least in modern design practice - through 'random variations'. The many designers of multi-storey car parks have had very definite (although not always completely rational) ideas about how their particular schemes could provide advantages over other designs.

This said there is nevertheless a sense in which all these designers have worked collectively, through the first half of the 20th century, to explore a world of slightly differing possibilities for car park architecture. At times they have, in effect, searched this world unsystematically, even 'blindly' - although after a while the comparative merits of some of the alternatives have become generally known. The fact that different designs were in direct economic competition was recognised very early. As the Architectural Record (1929: 182) put it: 'Because the parking garage business is still in its infancy, commercial garages must necessarily be extremely efficient from the economic standpoint if they are to compete with future buildings of improved character...'. And there is a sense in which external factors in the 'environment' of car parks, such as the cost of labour, the design of cars, and the changing preferences and concerns of car drivers have acted, at different times, to make certain designs of building more useable, efficient or profitable than others. In these limited senses then, the use of concepts borrowed from evolutionary biology has some validity. We will come back to these evolutionary issues at the end of the paper.

3. Elevator garages, and parking by attendants
Meanwhile let us look in some more detail at the history of high-rise car parks in the 20th century. Today it is general practice for drivers to park their own cars. This was not the case in the United States in the 1920s and '30s and even for some time after World War II. The early elevator garages were worked by attendants who moved the cars on and off the lifts (later the process was completely automated). Up to the 1950s it was normal also for attendants to park the cars in ramp garages. Once having parked a car, an attendant would slide to ground level down poles like those used by firemen. To get to the upper levels to retrieve a car, he would ascend by paternoster or 'manlift' (Figure 1).
It seems that Americans' reluctance to park their own cars in this period was partly to do with lack of driving skills and the failings of automobile technology. Early, low-powered models had difficulties on stiff inclines. It was believed that women in particular were daunted by the prospect of negotiating steep slopes and sharp turns. Two American authors writing in 1958 say for example that, with the introduction of automatic gear shifts, 'Women drivers no longer fear gear-changing or running backwards down ramps' (Baker and Funaro, 1958:116). Parking by skilled attendants had the minor advantage that bays and aisles could be made somewhat smaller than for customer parking. By contrast with the States, attendant parking was never popular in Europe. Klose (1965:33) says this was because '...the [European] motorist does not like to part with his car, and ... because rapid handling is impeded by the multiplicity of car types with different controls.'

In summary then, we can distinguish four classes of high-rise garage according to the means of access and how cars are parked:

- elevator garages, attendant parking
- elevator garages, automatic
- ramp garages, attendant parking
- ramp garages, customer parking.

As mentioned, elevator garages were being built in the USA in the 1920s and '30s, as for example the Pure Oil garage in Chicago, and the Kent garages in Chicago, New York and Cincinnati (Baker and Funaro, 1958). Typically, these buildings had half a dozen stalls clustered around each elevator on every level. The Kent Garage in New York accommodated 12 cars per lift per floor (Jakle and Sculle, 2004). In some cases, one elevator could carry several cars. Hill's Garage in Los Angeles for example, which opened in 1928, had three elevators each of which carried three automobiles (Longstreth, 1997). Cars were either driven from elevator to stall, or were pushed on dollies. The result was buildings with small footprints, which could be fitted onto expensive and constricted cen-
tral sites. But in order to get sufficient car places served by one or a few elevators to make the operation economic, it was necessary to build very high - up to 24 storeys at the highest. This increased the cost of construction.

Even more important, it meant that the process of parking and retrieving cars was extremely slow. This had the knock-on effect that, at peak times, a queue could develop at the entrance, and extra 'reservoir' space had to be provided at ground level for cars waiting to be parked. When picking up their cars at peak times, drivers could wait 20 minutes or more. One further weakness was that the elevators themselves were costly to maintain, and liable to occasional electrical or mechanical failure, in which case the cars were trapped. All these problems led to the general demise of the simple elevator type garage by the late 1930s. According to Jakle and Sculle (2004), all of Manhattan's elevator garages went bankrupt in the Depression. On the other hand an article in the Architectural Record (1958) mentions that two pre-War elevator garages were still operating in the 1950s, the New York Kent Garage and the Park-O-Mat in Washington DC. Müller (1925) in his book shows a number of theoretical schemes for elevator car parks with circular or octagonal plans - but these it seems were never built.

After the Second World War a new generation of elevator garages emerged, and a number of manufacturing companies were formed, some of them quite successful for a period. Their success depended on significant changes in design and methods of operation. One common feature was extensive automation, so that it was no longer necessary to employ large numbers of attendants - an important consideration given post-War increases in labour costs. The Zidpark system resembled the pre-War elevator garages, but with many elevators and their associated stalls, packed close together. Car drivers left their vehicles in the lifts at ground level. On each upper level there were four stalls associated with each lift, the cars being moved sideways into the stalls on dollies. The whole process was automatic, and was operated from a central control panel. Figure 2 shows a Zidpark garage built in Upper Thames Street, London in 1961.
In other systems such as those of the US-based Bowser Parking System and Pigeon Hole Parking companies, the key innovation was the introduction of elevators capable of moving vertically \textit{and horizontally} at the same time along an elongated central shaft or slot in the building, with parking places ranged - like pigeonholes, precisely - on either side (Figure 3). In this way, one elevator could serve a much-increased number of stalls on each level. Like the pre-War mechanical garages, such buildings were specially suited to restricted downtown sites. The Autosilo company of Heidelberg developed a very comparable type of pigeonhole system for the European market. The basic idea was not entirely new. Müller (1925) illustrates several proposals, and one actual completed building in Paris dating from the 1920s (Figure 4), with car parking bays on several storeys either side of a central top-lit hall; fixed elevators; and light moveable bridges to carry the cars along the hall. The post-War systems differed by virtue of having the lift itself move laterally, and under automatic control.

**Figure 3.** Principle of the 'pigeon hole' type garage, with a central elevator tower moving horizontally along a void between the car stalls (from Klose, 1965:67).

**Figure 4.** Elevator garage with moveable bridges for transferring cars from the elevator to the stalls, Paris, 1920s (from Müller, 1925: 70).
Bowser and Pigeon Hole came to be the main competing manufacturers of elevator garage systems in America. The first Pigeon Hole installation was built in 1950; the first Bowser garage in Des Moines, Iowa, in 1951. In the Pigeon Hole system the elevator tower moved on rails (Figure 5). In the Bowser system it was suspended from an overhead gantry. As Baker and Funaro (1958: 187) say, this lateral movement was ‘...the all-important difference between these elevator systems and those which proved unsuccessful in the Thirties.’ Bowser had attendants driving the cars from elevator to stall, and had cars packed two deep on one side of the elevator shaft, the back rows being offered to all-day parkers at lower rates (the penalty was that it was still sometimes necessary to move the cars in front to retrieve those behind). Pigeon Hole moved the cars automatically on dollies. Figure 6 shows the control panel for a Bowser garage. The structures of these buildings could be just minimal steel cages, and the stalls could have restricted widths and heights compared with those needed for driver parking. One general problem with mechanical garages, on the other hand, was that the stall sizes were fitted inflexibly to particular car dimensions, whereas stall dimensions could, to an extent, be adjusted in large ramp garages with wide structural spans, when fashions in car size changed.

Figure 5. Pigeon Hole garage serving a hotel in Harrisburg, Pennsylvania, 1950s (from Baker and Funaro, 1958: 88).

Figure 6. The control panel of a Bowser garage (from Klose, 1965: 58).
Yet further types of automatic parking system were developed by other companies using the principle of the paternoster or the Ferris wheel. Here the parking stalls were moved to meet the cars, rather than the other way round. An endless chain of stalls or cages was moved past the point at which the cars were loaded and unloaded (Figure 7). Westinghouse had been experimenting with a prototype Ferris wheel design as early as 1937. Such systems seem not to have met with much success, presumably because of the time taken for parking and retrieving cars in large installations. Klose says in 1965 'Up to now, such parking facilities have only been built as minor units'. Little more is heard of them.

This question of parking and retrieval times undoubtedly proved critical in the final showdown between elevator garages and ramp garages that took place in the 1960s. Table 1 is reproduced, with some adaptation, from Klose and gives operating statistics for fifteen multi-storey garages around the world. The figures were supplied by the builders and operators and should therefore perhaps be treated with a little caution. The overall picture is however clear enough. The table gives basic data in each case on number of floors and number of car places ('capacity'). The columns of special interest here however relate to the 'intake' and 'delivery' rates, i.e. the maximum rates at which cars can enter and leave the garage. These are given both as numbers of cars per hour, and as percentages of the total capacities of the buildings. Seven of the garages are elevator types (E) and eight are ramp types. Of the ramp garages, parking in two is by attendant (RA) and in six by the customers (RC).
The percentage intake rates for ramp garages with customer parking (RC) lie in the range 69 to 182%, while those for elevator garages (E) lie in the range 24 to 67% (the one exception being the London Zippark with a rate of 108%). That is to say, the customers are able to park their own cars in ramp garages much faster - typically of the order of three times faster - than cars can be parked in the elevator garages. The comparative rates for retrieving cars are similar to those for their delivery. This is even more important, since at elevator garages, returning drivers must sit and wait idly for their cars; while as Baker and Funaro (1958: 121) cannily point out '...if a customer is busy fetching his car, he will not notice how long it actually takes him to reach it.'

Meanwhile the parking and retrieval rates for the two ramp garages with attendant parking (RA) are comparable with those for elevator buildings. These rates in general depended directly on the number of attendants employed. It was always possible to increase the delivery rates by taking on more staff - but this in turn raised labour costs.
Customer parking in ramp garages therefore scored over other systems of operation in terms of typical speeds of delivery and retrieval. Another advantage, as we have seen, was that - since entry of customers to the garage was continuous - there was no need to provide extra reservoir space at the entrance. On top of this there was the question of costs. Customer parking by definition avoided almost all of the labour costs associated with attendant parking, and all of the capital and maintenance costs of the complex machinery involved in the automated systems. Elevators (and stairs) were still needed in tall garages, but only for the customers themselves, not their cars. The delivery and retrieval rates quoted for the London Zidpark garage in Table 1 are fast - faster indeed than many of the ramp garages. But these are achieved at the cost of providing 16 car-carrying elevators in a building with 464 places on just seven floors. All this confirms the conclusions of Baker and Funaro, writing in the late 1950s (1958: 117), that 'Operating costs of mechanical garages will be higher than self-parking ramp garages, but lower than ramp garages with attendant parking.' They add (p.164) that, in their opinion,'... the increasing cost of labor will soon make attendant parking unprofitable and inefficient in all but a very few special areas where land costs and receipts are both exceptionally high.'

These comparisons of entry rates, delivery rates and costs have demonstrated then, at least in broad terms if not with quantitative data in every respect, why elevator garages and attendant parking largely faded into history in the late 1960s. We are left with the question of the comparative merits of different detailed arrangements for ramp garages, where the cars are parked by the customers.

4. Ramp garages, with parking by customers

Customers want to get to empty spaces as quickly as they can, of course. But the situation is now slightly different from attendant parking. When cars are parked by attendants, there must be some sort of system like those for checking coats in cloakrooms: that is to say the attendants must keep a record of where all the customers' cars are parked so far, and which places remain empty. When parking new cars, they can then go directly to the nearest vacant positions. A customer who parks his or her own car does not have this information, and must search for a place. He or she will be able to do this the more effectively, if the entry route provides a tour of the park, level by level. When the customer comes out again however, there is no need for a tour, and he or she will want to go directly to the exit. Notice that in Table 1, in two of the customer parking ramp garages (RC) the rate of exit from the park is faster than that of entry, for just this reason (in a third case however, the garage in Auckland NZ, it is slower to get out than get in, which is perplexing).

Both on the way in and on the way out, the flow of cars will be smoother if streams of traffic do not cross, and if cul-de-sacs are avoided, where drivers are obliged to reverse. There may be advantages to one-way traffic, where this is feasible, in creating simpler, less obstructed movement patterns. In some designs the car stalls are arranged alongside the ramps ('adjacent parking') so that cars being manoeuvred in and out of stalls block the traffic flow; while in others the ramps are free of parking (they are 'clearway ramps'). These are some of the ways in which the various arrangements of ramp car park may be made more or less efficient and smooth running. Klose (1965: 36) summarises
the ‘optimal solution for the self-parking motorist’: ‘On arrival, the motorist is taken past all the parking stalls; there is no oncoming traffic, and the departing cars can leave via the exit ramp, rapidly and without hindering the parking manoeuvres of other cars.’

Books on car park design tend to present the variety of possible ramp layouts in a bewildering array of isometric diagrams, festooned with directional arrows and dotted movement paths. In some types the three-dimensional geometry is indeed complex. At heart however there are just a few basic organising principles. The plan for the remaining part of this paper is to make a measured comparison, on a common basis, of fourteen theoretical designs of garage, each representative of a different ramp system. Together these cover the great majority of sub-types appearing in the literature up to the 1960s. More details are given in Appendix A.

The various features will be explained as we proceed, together with some of the history of each generic design. All these notional buildings (with one exception) are on four storeys and have a simple rectangular plan with the same overall dimensions, 32 x 75m. They have capacities between 350 and 450 cars, not untypical of the immediate post-War period (compare Table 1). Axonometric drawings of all fourteen garages, labelled A to N, are presented in Figure 8. The designs are compared numerically on three basic criteria, whose significance should by now be clear:

the length of a complete tour of all car spaces;
the mean distance of car spaces from the entrance and from the exit;
the mean floor area per car space.

Figure 8. Axonometric drawings of all fourteen theoretical designs of ramp garage, A to N (see text for details).

This last measure is intended as a proxy for construction cost, in the absence of real data (albeit a rather rough proxy, for reasons to be discussed). In the different designs, the number of car spaces varies somewhat, because of the exigencies of the ramp layouts. The total floor area can also differ because of the presence of internal voids or externally attached ramps.
5. Comparison of theoretical designs of ramp garage

In order for the comparison to be as fair as possible, common standards have been set for key dimensions throughout. The size of every car space has been fixed at 2.5 x 5m, which was normal in post-War European practice - although bay sizes in American garages tended to be larger. The bays can in principle be laid out at different angles to the aisles. When set at 45°, the stalls in adjacent rows can be fitted together into parquet-like or herringbone patterns (the arrangement is compatible only with one-way traffic). It is easier to manoeuvre in and out of angled bays, and the aisles can be made narrower than with 90° parking. On the other hand a series of laborious analyses made in the 1950s seemed to show that the arrangement which packs the most spaces into the smallest floor area is 90° parking - partly because angled bays waste space at the ends of the rows (see for example the tables in Baker and Funaro (1958: 170-179). In the theoretical buildings the parking is therefore laid out at 90° to the aisles throughout.

In all but one of the buildings the basic layout on each floor is in four rows of parking stalls, served by two aisles whose width - for two-way circulation - is 6m. This gives the standard overall building width of 32m. Most authorities recommend maximum gradients for access ramps of between 10 and 15% (in the earliest ramp garages the gradients were often shallower, for reasons already explained). For the present experiments we assume a maximum gradient of 12.5%. Given a 2.5m floor-to-floor height, this gives a straight ramp of 20m length (in plan) for a full storey, and 10m length for a half storey. These dimensions fit nicely with the car bays. In some designs there are straight ramps that run the length of the building. The 75m plan dimension allows for such a longitudinal ramp to rise the full three storeys - hence the decision to make all the buildings this length. In every case the entrances and exits are at the ends of the building (sometimes at the same end).

One basic difference between the sub-types of ramp garage is in the nature of their floor plates. These can be simple flat floors on each level, as in designs A to G. The floors themselves can be given a continuous gentle slope, and can serve as both ramps and parking surfaces, as in designs H and I. Or the floor levels can be split and connected with half-length ramps, as in designs J to N.

Scheme A has two straight one-way ramps on either side of the garage. These are very shallow and rise only one storey in the building's entire length. Cars entering take one of the side ramps to the first floor, return along the central aisle, take a second ramp to the second floor, and so on. Cars leaving go down the matching ramps on the opposite side of the building. The arrangement is compatible only with two long rows of parking bays per floor (plus two short rows at the ends), giving a plan width of 22m. In order to compensate in the analysis, this building (alone) has been increased from four to six floors, so that the total number of parking spaces is comparable with other designs. Such shallow ramps are characteristic of some of the very earliest ramp garages of the 1920s and '30s. Müller (1925) for example illustrates a garage built for postal vehicles in Budapest in the early '20s (Figure 9) with long straight single-storey ramps either side of a central void.
The designs of garages B and C again have straight longitudinal ramps, but much shorter than in A. Scheme B has two-way ramps. Scheme C has separate one-way up and down ramps, sloped in opposite directions. Such ramp systems were also found in early garages. *The Architectural Record* (1929: 183) gives illustrative examples of both types (but without identifying the actual buildings).

Schemes D and E have long straight ramps like garage A, but now on the exterior. In garage D cars enter from the ramp through doors at ‘landings’ on the successive levels, and exit via the same doors. Garage E is essentially the same, but with two one-way straight ramps on either side of the building, one for entry and the other for exit. Figure 10 shows a particularly handsome version of this arrangement, designed by Paul Schneider-Esleben and built in Düsseldorf in 1953.
Schemes F and G have flat floors accessed by helical ramps. Scheme F has two separate one-way ramps attached externally at the opposite ends of the building, one for entering and one for leaving. The Venice Autorimessa has ramps of this kind (Figure 11). In scheme G there are again two helical one-way ramps, one for entry and one for exit, but now fitted into a rectangular area within the body of the building. Each rises two floors in a full turn, and the two ramps are intertwined. The positioning is such that the points of entry and exit are on opposite sides of the ramps.

Schemes H and I have the gradually sloped floors that are sometimes referred to by the rather curious name of ‘non-dissipative ramps’. In effect the entire structure is a wide access ramp, on which the cars are also parked. The maximum slope generally recommended for such floors is 5%: the two designs meet this standard. One can think of these buildings as very tightly wound helical roads with ‘kerbside’ parking. As Louis Kahn says of his own cylindrical designs, which are of this general type, ‘... the street wants to be a building’. Scheme H consists of a simple single two-way helix. Figure 12 illustrates the Rupert Street car park in Bristol, which is of this type but has an oval ‘racetrack’ plan. The designer was R Jelinek-Karl, and the garage was built in 1960. In scheme I two helices interlock, and movement is one-way up on one helix, and one-way down on the other. Cars can move between the helices at the central cross-aisles.
Finally, buildings J to N are split-level designs, in which the ramps are all half-length and rise half a storey. These are D'Humy ramps, named after their inventor Fernand E D'Humy of Englewood, New Jersey, who received his first patent in 1919 and took out three more in the early 1920s. D'Humy was responsible for other inventions in lighting, the telegraph, and dirigibles; but it was his parking ramps that brought him a modest immortality. The Ramp Buildings Corporation of New York was set up in 1920 to exploit d'Humy's designs (Jakle and Sculle, 2004). Figure 13 shows a D'Humy ramp in a garage built by the company, dating from this period (notice the Model T Fords). Figure 14 illustrates a spare minimalist version in Miami, Florida, from 1949, by the architect Robert Law Weed (this has not two but three split level parking zones, joined by two sets of ramps).

As Klose (1965) says of this garage,'...the cars are elegantly offered on a platter...'. In our scheme J, the levels are split across the building, and the ramps are in the centre of the plan and aligned longitudinally. In schemes K, L, M and N the levels are all split longitudinally, and the ramps run crossways. The different positioning and direction of these ramps is critical, as we shall see.

Figure 13. D'Humy ramp in a garage built by the Ramp Buildings Corporation in the early 1920s (from Müller, 1925: 35).

Total floor areas including ramps have been measured for all fourteen schemes. In order to analyse the buildings' access patterns, to clarify them visually, and to help measure distances, a special representation has been devised. The patterns are depicted as networks in the graph-theoretic sense, with edges corresponding to the aisles and ramps, and vertices corresponding to their junctions. These networks have been drawn with the edges at their true lengths to scale, and according to a convention inspired by the so-called 'justified graphs' used in space syntax studies of buildings by Hillier and Hanson (1984: see in particular Chapter 4). For the pattern of entry to a garage, the ground level entrance point is placed on the left of the diagram. Aisles and ramps are then drawn 'stretched out' horizontally towards the right, connected in the order that they are reached via the shortest routes.

The total distance travelled from the entrance to any point in the network (the 'metric depth' of that point) can then be measured on a horizontal scale. For clarity in the diagrams, branching 'parallel' routes in the network are separated vertically by using curved joining lines - but the vertical distances involved here are not counted in the depth measurements. Junctions and (straightened out) 90º turns are both shown as hollow circles. Ramps are shown in heavier line than aisles. From these 'justified' network diagrams it is very straightforward to calculate the mean distances of all car spaces from the entrance (since those spaces are regularly distributed along the aisles), as well as the lengths of complete tours. In some cases the networks for both entering and leaving the garage are the same, because of symmetries in the plan. In other cases the presence of one-way aisles and ramps, and the positioning of ramps, can mean that the routes and mean depths from the entrance are not the same as those from the exit - in which case two different diagrams are drawn, for distances going in and coming out.

Figure 15 gives diagrams in this format for all fourteen buildings. From these visualisations of the overall structure of the circulation patterns it is easy to see where a layout provides a continuous uninterrupted tour of the building (the network consists of a single unbranching route); where a tour involves going up and reversing back down cul-de-sacs (the network is tree-like); or where a tour or route to the exit involves crossings (the network contains cycles).
6. Comparative performance of the theoretical garage designs

Table 2 gives numerical results, for all fourteen buildings, for the mean distances of all car places from entrance and exit (m), the length of a tour (m), and the mean floor area per car space (m²). All of these values should ideally be low - as we have seen - in an efficient, cost-effective design. The table shows that tours of the garages are shortest where they follow a simple helical path around the longitudinal and cross aisles. This is the case, naturally, for the two helical sloped floor schemes, H and I, as well as for two of the split-level garages, J and N. Routes to the exit are shortest on average when drivers can get quickly from any car space to a ramp that then descends directly to the ground - whether this ramp is straight (as in schemes D and E) or helical (as in schemes F, G and, in effect, scheme N). In the case of designs D, E, F and G however, the routes to these exit ramps involve crossings that could cause delays.

<table>
<thead>
<tr>
<th>Garage type</th>
<th>Capacity</th>
<th>Mean depth (m) on entry</th>
<th>Mean depth (m) on exit</th>
<th>Length of tour (m) on entry</th>
<th>Mean area / car place (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Long straight ramps each rising one floor; in one side, out the other (6 floors)</td>
<td>372</td>
<td>382</td>
<td>382</td>
<td>969</td>
<td>26.6</td>
</tr>
<tr>
<td>B. Two-way internal straight ramps</td>
<td>384</td>
<td>172</td>
<td>150</td>
<td>808</td>
<td>25.4</td>
</tr>
<tr>
<td>C. Opposed internal one-way straight ramps</td>
<td>384</td>
<td>150</td>
<td>150</td>
<td>778</td>
<td>25.4</td>
</tr>
<tr>
<td>D. External straight ramp to all floors; in and out same side</td>
<td>434</td>
<td>86.1</td>
<td>86.1</td>
<td>820</td>
<td>23.2</td>
</tr>
<tr>
<td>E. Two external straight ramps to all floors; in one side, out the other</td>
<td>428</td>
<td>86.2</td>
<td>86.2</td>
<td>816</td>
<td>23.5</td>
</tr>
<tr>
<td>F. Two external helical ramps; one in, one out</td>
<td>448</td>
<td>120</td>
<td>120</td>
<td>835</td>
<td>24.0</td>
</tr>
<tr>
<td>G. Two external intertwined helical ramps, rising one floor in half a turn</td>
<td>354</td>
<td>99</td>
<td>94</td>
<td>788</td>
<td>25.6</td>
</tr>
<tr>
<td>H. Sloped floor with two-way traffic</td>
<td>448</td>
<td>344</td>
<td>344</td>
<td>692</td>
<td>21.4</td>
</tr>
<tr>
<td>I. Sloped floor with one-way traffic</td>
<td>436</td>
<td>306</td>
<td>200</td>
<td>748</td>
<td>22.0</td>
</tr>
<tr>
<td>J. Split levels with central longitudinal D'Humy ramps</td>
<td>352</td>
<td>143</td>
<td>143</td>
<td>713</td>
<td>25.0</td>
</tr>
<tr>
<td>K. Split levels with lateral D'Humy ramps, level 1</td>
<td>432</td>
<td>200</td>
<td>200</td>
<td>956</td>
<td>21.8</td>
</tr>
<tr>
<td>L. Split levels with lateral D'Humy ramps, level 2</td>
<td>432</td>
<td>266</td>
<td>266</td>
<td>814</td>
<td>21.8</td>
</tr>
<tr>
<td>M. Split levels with lateral D'Humy ramps, level 3</td>
<td>432</td>
<td>267</td>
<td>210</td>
<td>862</td>
<td>21.9</td>
</tr>
<tr>
<td>N. Split levels with lateral D'Humy ramps, level 4</td>
<td>432</td>
<td>335</td>
<td>123</td>
<td>669</td>
<td>21.8</td>
</tr>
</tbody>
</table>

Table 2: Statistics for the eleven theoretical designs of ramp garage.

The mean floor area per car space is lowest in the sloped floor garages H and I and in the D'Humy ramp garages K, L, M and N. Earlier it was suggested that this value could be a rough indicator of construction cost. It is likely however - at least in the context of later 20th century construction practice - to underestimate the relative costs for garages with helical ramps, since these require more complex formwork for the in situ concrete. The split-level garages are simple to build,
since they have flat floors, and the D’Humy ramps themselves are just tilted rectangular slabs. Indeed in the 1960s the Tishman Research Corporation of New York developed a system of prefabricated pre-cast concrete units for D’Humy ramp garages, for which they claimed costs per car place competitive with rival methods (Klose, 1965: 106-110).

The lists below show how all fourteen garages are ranked on the three most important measures:

<table>
<thead>
<tr>
<th>Measure</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean area per car (m²)</td>
<td>H, L, M, I, D, E, F, J, B, G, A</td>
<td>N</td>
</tr>
<tr>
<td>Mean depth (m) on exit</td>
<td>D, E, G, F, N, J, B, K, I, M, L, H, A</td>
<td>C</td>
</tr>
<tr>
<td>Length of entry tour (m)</td>
<td>N, H, J, I, C, G, B, L, E, D, F, M, K, A</td>
<td></td>
</tr>
</tbody>
</table>

No outstanding winner emerges, way ahead of the field, from this analysis. The two schemes with external straight ramps D and E have short distances to the exit - the shortest of all designs - but have long tours, and what is more, these tours have many crossings. The two schemes with sloping floors, H and I, score well on floor area per car, and on length and simplicity of the entry tour; but the mean distance to the exit is very long in both cases.

The scheme with what is undoubtedly the best overall performance however in these terms is the split-level design N with D’Humy ramps. In this layout, two widely spaced ramps on each floor provide for the entry tour, while two closely spaced ramps, offset towards the exit end of the building, create a fast - in effect helical - route out. It is this special disposition of the ramps that gives scheme N the edge over the other split floor designs. It has the shortest tour, the equal second lowest floor area per car, and the fifth shortest mean distance to the exit - and even this, only some 40m shorter than the best scheme. In D’Humy ramp garages in practice it is actually possible to pack even more cars onto a given site area than in the examples here, since the floors can be slightly overlapped so that the bonnets [American: hoods] of one row of cars hang over the bonnets or boots [American: trunks] of the cars below (compare Figure 14). This comparative 'efficiency' of D’Humy ramp garages had been already recognised by the 1920s (Architectural Record, 1929). As we saw earlier, split level car parks of this general kind had come to dominate the field, at least in the United States, by the late 1950s. Our experimental comparison shows why this happened.

This exercise has of course been limited and to an extent artificial. The comparative results would differ somewhat with altered assumptions about dimensional standards and detailed layout. More importantly, two considerations, not taken account of here, would affect the suitability in practice of the different designs to different circumstances. The first is the size and shape of the given site, and its relationship to adjoining streets. There is a basic modular dimension in car park layout, given by the width of one aisle plus the depths of the two rows of stalls to which the aisle gives access. Ricker (1957) refers to this as the 'unit parking depth', Crest et al (1996) as the width of one 'parking
bay’. In our designs here the module is 16m, repeated twice to give the 32m width of each building. It will be clear that the actual dimensions of any given site will determine the possible number of unit parking depths that can be fitted in, and will constrain the directions in which the aisles run. In awkward cases, this might lead to inefficiencies in the use of space. The site might further determine the positions of exits and entrances, and so lead to a choice of ramp positions that might not be optimal on other criteria. In such situations, as Baker and Funaro (1958: 115) say, 'Figures of average space per car are often unimportant, and even deceptive'. Our theoretical buildings have been designed with no concern for these exigencies of siting.

The second factor ignored here is the special character of the customers for whom the garages might cater. We have assumed some kind of general non-specific parking demand. In reality the users might be office workers leaving their cars all day, shoppers parking for a few hours, theatre-goers parking for the evening, hotel guests leaving their cars overnight, or passengers at airports leaving their cars for many days. The patterns in time in which these users would typically arrive and depart would vary accordingly. Car park designers during the later 20th century have worked to tailor buildings more carefully to these distinctive markets and their peak demands. We have emphasised the problem of customers searching the garage for empty spaces. But, for example, when a garage caters to the same group of office workers every day, they get to know the layout, and the ramp system does not have to be quite so legible and easily navigable as for drivers to whom the garage is unfamiliar.

Another trend over the last fifty years has been a general increase in garage size. As Chrest et al (1996) say, 'in the past' - i.e. in the mid-20th century - an average American car parking structure served 300 to 500 cars, and a 1000 car garage was 'huge'. At the start of the 21st century, structures for 1000 to 3000 cars are not unusual, and garages have been built for up to 12,000 cars. In these much larger garages, new types of ramp layout have become possible. The basic helical sloped floor design (our scheme H) for example can be doubled end-to-end, or extended laterally into three or four unit parking depths.

Different performance criteria begin to apply. In the experiments reported here, distances measured in garage layouts have been taken as reasonable proxies for times taken entering and leaving. Ricker (1957) pioneered actual time-and-motion studies in different types of garage, using a stopwatch and taking movies. And in the late 1960s the Transport and Road Research Laboratory in England developed a theoretical model that related together aisle and ramp design, angle of parking, one-way or two-way movement, type of user, and overall plan layout, with which it was possible to predict rates of traffic flow, in particular at times of peak demand (Ellson, 1984). The issue of peak flow has since come to be a central concern in car park design.
When garages are made extremely large, there is a real danger of drivers getting disoriented, or being unable to find their cars again. So legibility of layout - irrespective of any signing - becomes another key design objective. Some layouts can be preferable on grounds of security, as for example when drivers can oversee large parts of each parking floor without obstructions.

For all these reasons, the simple results of the comparative experiment reported here would not apply to larger garages, or garages for some more specialised market niches, built later in the 20th century. An equivalent approach could no doubt be carried out to compare such designs, but space here does not allow. Even so, it is worth noting that the discussion of different generic garage layouts and their merits in today's leading design handbook (Chrest et al., 1996) concentrates almost exclusively on different sloping floor and split level types - more basic forms of which beat the competition in the analysis presented above.

7. The evolution of the multi-storey garage as an instance of 'evolutionary radiation'

To go back to the analogies with natural evolution introduced at the start of the paper: the case of the multi-storey garage has some affinities with what is known by Darwinists as evolutionary radiation. The most celebrated biological example is the variety of slightly differing species of finch that Darwin himself discovered on the Galapagos Islands, and that provided him with crucial evidence for the theory of natural selection. It seemed that one species of seed-eating finch had originally migrated from the mainland, to find an environment with little direct competition from other bird species, and a variety of available sources of food. In the car park analogy, this novel environment is the completely new demand for car storage buildings arising in the 1920s.

The original Galapagos species of finch evolved over time into as many as fourteen distinct species, adapted differently in bodily form - especially in the shape of the beak - to eating cactuses and insects as well as seeds, and to living at ground level as well as in trees. The equivalent in the evolution of garages is the variety of different detailed designs of ramp and elevator building that emerged between the World Wars. In both cases, biological and architectural, the 'empty' environment provokes a flowering of diversity.

The separate species of Galapagos finch were able to coexist, since they were no longer in competition for the exact same habitat and food supply. This is the phenomenon of adaptive radiation, into different ecological niches. What is different in the case of garages is that most of the designs were in direct competition for a general market in short-term parking provision in cities. This is why many of them were abandoned. There were nevertheless some separate commercial niches (the same word and concept in economics as in biology) in which certain specialised designs could flourish in relative isolation. Elevator garages were particularly adapted to small central sites onto which ramp garages could not be squeezed. Indeed, the elevator garage survives in similar special
niches today - despite its general disappearance otherwise - in locations with extremely high land values, and for all-day or all-night parking where the speed of retrieval of cars is not critical, as in some residential areas of Tokyo, or associated with city centre hotels.

The initial variety of garage designs in the 1920s and '30s was not evolved through 'artificial selection', but was produced rapidly through the inventiveness of many designers. It turned out, nevertheless, that some designs possessed greater 'fitness' for the parking environment, and competition began to select for them. Over time this general economic and social environment changed - as already described - in costs of labour, in costs of construction, in the willingness or not of drivers to park their own cars - in ways which at successive periods favoured one species of garage over another. Elevator garages went extinct, were reborn, and went nearly extinct for a second time. Attendant parking disappeared, as did some of the ramp types. The split-level garage beat much of the competition. As Jakle and Sculle (2004: 133) put it, 'Parking garages evolved considerably to the midpoint of the twentieth century, but never teleologically. Economic ebbs and flows opened entrepreneurial opportunities as well as closing them with what seemed great suddenness'.

To take this type of analysis further it would be necessary to have statistics for the entire populations of the different designs, for successive decades of the 20th century. For garages such data would be very laborious to collect. There are other building types where population data are more or less complete however, such as shopping arcades (Geist, 1983; MacKeith, 1986) and which might be used for comparable evolutionary analyses - in the case of arcades, as they first emerged as a new type in 18th century Paris, and eventually lost the competition with department and other variety stores and became extinct at the end of the 19th century. With garages we can at least say something about the dates at which separate species originated and disappeared, if not about the total numbers of individuals within each species.

There were temporal changes in the economic and social environment of multi-storey garages. There were also differences between parts of the world at the same point in time. Attendant parking was never popular in Europe, as it was in the USA. I have not gone deeply into the complex subject of construction costs: but it is clear for example that varying costs of building labour between different countries have altered the relative competitiveness of in situ concrete as a structural material, in ways that will have been relevant to the capital costs of ramped garages. The multi-storey car park environment changed again in the second half of the 20th century, and is likely to continue to alter in the future. New designs may be evolved gradually from old ones; or quite unprecedented novelty may be introduced overnight. This is one of the many differences between biological evolution and the evolution of artefacts. Another is that, when a natural species goes extinct it is lost forever, whereas extinct types of building can come back from the dead.
8. Notes
1. As so often with the identification of the supposed point of origin of innovations, there are earlier precedents, of a kind. Multi-storey stables were built for horses in the 19th century, near London railway terminals, with access by ramps to upper levels. In America, livery stables were converted to garages in the 1910s and '20s.
2. German authors went on to make a speciality of this minor branch of architectural literature, as the bibliography here shows.
3. Baker and Funaro (1958) recommend a bay to fit most Fifties American models of car, with dimensions of 9'0" x 19'0" (2.7 x 5.8m). Ricker (1957) recommends 8'6" x 18'0" (2.6 x 5.5m).
4. The idea that 90º parking is always the most efficient in space became accepted wisdom among garage planners. It has however been questioned more recently, as in Smith (1996: 37-39) who shows that angled bays can in certain circumstances save space, since the one-way aisles can be narrower than two-way aisles.
5. Another early example of split levels with half-storey ramps was the Mutual Garage on Olive Street, Los Angeles, opened in 1924 (See Longstreth, 1997: 47).
6. The lengths of ramps have been measured in plan, not as actual distances up and down the sloping surfaces. Since this approximation is made for all fourteen cases, it should not greatly affect the comparative results.

9. Acknowledgement
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Appendix A: Types of garage listed in different publications cited

The 1929 *Architectural Record* article (p.183) illustrates actual garages corresponding to my types B and C, a single D’Humy ramp design, and garages with internal helical ramps comparable to my scheme G although much more wasteful of space. (It also shows a plan for a multi-storey garage within the core of an office building. This ‘park at your desk’ idea was revived in the 1950s. Baker and Funaro (1958) illustrate a design by LeRoy L Warner for the Cafritz building in Washington D C, with parking at the centre of the plan and offices around the periphery. It is not clear from their account whether this was actually built.) Interestingly the *Architectural Record* compares these types for their ‘efficiency’, i.e. floor area per car space, on the basis of theoretical plans with standard dimensions of 100 x 200 feet. These are not however illustrated.

*Architectural Forum* (1953: 126) simply mentions four generic types: ‘straight ramp, staggered floor or split ramp, spiral ramp and sloped floor’. *Architectural Record* (1958) gives isometric drawings of thirteen types. These include straight ramp designs comparable to my schemes A, B and C; sloped floor schemes equivalent to my H and I; two garages with variants of the type of internal helical ramp in my scheme G; three D’Humy ramp garages comparable to my schemes J to N; and a D’Humy ramp design with three staggered floors as in Figure 14. This last type is however intrinsically larger than the garages compared here.

Comparing the types analysed here with those listed in textbooks of the 1950s and ’60s, I include 7 out of 11 generic layouts shown by Ricker (1957: 102-114), 8 out of the 14 layouts shown by Vahlefeld and Jacques (1960: 21-23) and all 9 layouts shown by Klose (1965:30-31). Ricker has several designs with lateral straight ramps that differ slightly from those compared in this exercise; another three-level staggered floor scheme; and a design with a semi-circular ramp rising one floor in 180º, otherwise similar to my scheme F. The types omitted here but included in Vahlefeld and Jacques’s enumeration are mostly buildings arranged around central courtyards or atria (their Figures 4, 8, 9, 13 and 14). Such buildings have their inspiration perhaps in courtyard office buildings or palazzi, with the car ramp taking the place of the grand central staircase. They provide good natural lighting; but tours and mean distances to entry and exit are necessarily longer than in deep-plan buildings without courts. Also excluded is a garage with long straight ramps each rising one floor (their Figure 2) that has some affinities with, but is not identical to, my scheme A. Klose (1965:37) shows sloped floor garages with attached rapid exit ramps, both straight and helical. These would improve exit rates over my schemes H and I, although on the other hand they would increase construction costs.
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